Macromolecules **2006,** *39,* 5729−5737

Monodisperse Micrometer-Size Carboxyl-Functionalized Polystyrene Particles Obtained by Two-Stage Dispersion Polymerization

Jing-She Song, Leonid Chagal, and Mitchell A. Winnik*

Department of Chemistry, 80 St. George Street, University of Toronto, Toronto, ON M5S 3H6 Canada

Received October 31, 2005; Revised Manuscript Received May 23, 2006

ABSTRACT: Monodisperse carboxylated micrometer-sized polystyrene particles were synthesized by dispersion polymerization of styrene in ethanol and in 95% ethanol−water in the presence of acrylic acid (AA) as a functional comonomer. When AA was present at the onset of the reaction, the resulting particles had an increased particle size and a broader size distribution than those prepared in the absence of AA. If, however, the addition of AA was delayed ca. 1 h, so that the particle nucleation stage was complete, then 2 wt % AA, dissolved in monomer plus solvent, could be added to the reaction without a deleterious effect on particle formation. When larger amounts of AA (e.g., 4 wt % based on styrene) were added, most resulting particles became unstable and coagulated if PVP55 ($M_w \approx 55000$) was used as the stabilizer. Some evidence points to interaction between −COOH groups on the particles as the origin of particle aggregation. Improved colloidal stability was achieved by decreasing the solids content, increasing the polarity of the medium, and switching to PVP360 ($M_w \approx 360000$) as the polymeric stabilizer. Coagulum-free particles with a very narrow size distribution containing 2%, 4%, and 6 wt % AA could be obtained in this way. Under these conditions, adding different amounts of AA in the particle growth stage did not change the particle size or size distribution.

Introduction

Functional polymer particles with various reactive groups on the surface have extensive applications in a variety of fields that include inks and coatings, chromatography, protein synthesis, and biomedical analysis. [1−5] Particles with submicrometer dimensions are most commonly prepared by emulsion polymerization. Emulsifier-free emulsion polymerization is particularly effective for preparing functional polymer particles with a very narrow size distribution, with diameters in the range 400−800 nm.[6] For many polymer particle applications in medical diagnostics, particles with micrometer dimensions are important. These are most commonly prepared by the seeded swelling method developed originally by Ugelstad.[7]

The carboxyl group is one of the most important surface functional groups for particles intended for biomedical or biodiagnostic applications. This group is relatively easy to derivatize using water-soluble coupling agents (e.g., carbodiimide reagents). In emulsion polymerization, the introduction of surface carboxyl functionality onto polystyrene (PS) particles can be achieved by copolymerization of styrene with carboxyl-containing comonomers such as methacrylic acid (MAA) or acrylic acid (AA). Seeded emulsion polymerization allows one to obtain particles with the surface enriched in carboxyl groups. This type of polymerization works very well for submicron particles, but is difficult to extend to larger particles. In this paper, we are interested in particles with micrometer dimensions, a very narrow size distribution, and −COOH groups on the surface available for functionalization.

Dispersion polymerization is in principle a very attractive method for preparing polymer beads with diameters in the range of 1−15 μm.[8−12] Traditional dispersion polymerization involves a single step reaction with a simple synthesis protocol in which all the reactants are mixed and heated, and often leads to particles with an exceptionally narrow size distribution. The preparation of monodisperse homopolymer particles by dispersion polymerization has been extensively studied, especially for PS and poly(methyl methacrylate) (PMMA). Typical reaction conditions consist of monomer and poly(vinylpyrrolidone) (PVP) as a polymeric stabilizer dissolved in ethanol (methanol for PMMA), heated in the presence of a free radical initiator. Corresponding copolymerization reactions are much more troublesome. Relatively few studies have been reported,[13−17] and these have shown that dispersion polymerization is highly sensitive to small changes in reaction conditions. Ober and Lok[14] and Horák et al.[15] carried out detailed studies of the dispersion copolymerization of styrene and *n*-butyl methacrylate (BMA) in ethanol/water mixtures. Sáenz and Asua[16,17] investigated the kinetics of the dispersion copolymerization of styrene and butyl acrylate (BA) and examined in detail the morphology of resultant particles. Recently, Cao et al.[18] prepared a series of micrometer-sized functional uniform PMMA particles by dispersion copolymerization. These papers showed that the presence of comonomers changed the particle size and broadened the size distribution. Not only can the polymerization behavior change in the presence of a second monomer in the reaction system but also even different comonomer ratios have to be treated as new polymerization systems from the perspective of optimizing reaction conditions.

The situation is more subtle when only small amounts of a second monomer are added. Some monomers, such as polymerizable derivatives of fluorescent dyes, chain transfer agents, or cross-linking agents can seriously disrupt the particle formation process when present at only 1 or 2 wt % in the initial reaction mixture.[9,13,19,20] Small amounts of polar monomers have a more benign effect. Twenty years ago, in experiments that would now be considered exploratory, Tseng et al.[13] reported dispersion copolymerization of styrene with a variety of polar comonomers. They were interested in understanding, among other things, the role of surface active co-stabilizers that are often added to a dispersion polymerization recipe. In their dispersion polymerization of styrene in ethanol, using PVP40 ($M_w \approx 40000$) as the polymeric stabilizer, they obtained a very

---

* Correspondence to M. A. Winnik; E-mail: mwinnik@chem.utoronto.ca

10.1021/ma052330f CCC: $33.50

narrow particle size distribution if they included 0.5 wt % of an anionic or nonionic surfactant or cetyl alcohol, but a broad size distribution if no costabilizer was present. They found that they could replace the costabilizer with 1 wt % (based on styrene) of a polar monomer such as methacrylic acid, hydroxyethyl acrylate, acrylamide, or even a vinyl-substituted crown ether. The particle size distribution obtained was narrow, but the size differed for each of these monomers. Yang et al.[21] studied the dispersion copolymerization of styrene with AA. They used somewhat larger amounts of AA than Tseng et al.[13] and found that with increasing amounts of AA in the monomer mixture, the resulting particle size increased and the particle size distribution became broader. In addition, the onset of turbidity was delayed, suggesting that the AA interfered with the particle nucleation stage. At higher levels of AA ($>$10 wt %), no particles formed, and a gel-like product was obtained.

Some authors have shown that dispersion polymerization of styrene in ethanol can be carried out with poly(acrylic acid) as the polymeric stabilizer. This approach produces particles with many carboxylic acid groups at the surface. Our interest is in gaining control of dispersion copolymerization to introduce carboxylic acids via a comonomer such as AA without significant perturbation of the particle size and without loss of the narrow size distribution that one can obtain by dispersion polymerization.

Our approach is based upon our recent discovery that many of the problems associated with dispersion copolymerization could be avoided if one delayed addition of the second monomer until the nucleation stage was complete and the particle number in the reaction became constant. It has been known for years that the nucleation stage of dispersion polymerization occurs early in the reaction. The very narrow size distribution of the particles obtained is an indication that nuclei with a narrow range of sizes form early in the reaction, followed by a long particle growth stage. The dynamic light scattering studies of the El-Aasser group establish that the nuclei that determine the final number of particles in the reaction form by a rapid aggregation of smaller, colloidally unstable particles produced by collapse and aggregation of growing polymer chains in the continuous medium. The detailed simulations of polymerization and particle growth kinetics by Yasuda et al.[22] demonstrate that the nucleation stage of dispersion polymerization of styrene in ethanol is complete at less than 1% monomer conversion, which for styrene under our reaction conditions (70 °C) corresponds to less than 15 min reaction time. There is good experimental evidence that the number of particles present in the reaction is constant from 10% conversion until the end of the reaction.[23,24] One imagines that only technical difficulties have prevented experimental confirmation of the Yasuda et al. prediction of constant particle number down to 1% conversion.

We call our methodology “two-stage” dispersion polymerization.[25] By delaying the addition to the reaction of various problematic comonomers until about 3% monomer conversion, for dispersion copolymerization of styrene in ethanol, we were able to prepare monodisperse particles containing a covalently bound fluorescent dye, and PS particles cross-linked with 1 mol % ethylene glycol dimethacrylate (EGDMA). In these reactions, we found it advantageous to add the dye comonomer or cross-linking agent along with additional styrene and ethanol. The resulting particles maintained the same particle number and the narrow size distribution as if the problematic monomer had not been added. The particle size could be adjusted according to the amount of styrene added in the second stage.

Table 1. Recipes for the Dispersion Polymerization of Styrene with PVP55 and Acrylic Acid in Ethanol

	amounts (g)				
		two-stage reactions			
materials	one-stage	1st stage	2nd stage	1st stage	2nd stage
styrene	6.25	6.25	6.25 (0) [a]	3.0	3.0
acrylic acid	0.063		0.25[b]	0	0.24[c]
ethanol or 95% ethanol	18.75	18.75	18.75 (8.0)[a]	16.95	16.95
PVP55	1.0	1.0		0.48	
TX305	0.35	0.35		0.15	
AMBN	0.25	0.25		0.12	

[a] 95% ethanol/water (w/w); no styrene added in the second stage. [b] 2 wt % based on styrene. [c] 4 wt % based on styrene.

The fundamental idea of this approach is that the particle nucleation stage is much more sensitive than the particle growth stage of the reaction. Deferred monomer addition avoids interference with the nucleation stage. One still has to contend with factors that affect the particle growth stage. For example, in the synthesis of cross-linked particles using divinylbenzene or more than 1 mol % EGDMA, other steps had to be taken in terms of timing the addition of the cross-linking agent to maintain particle swellability during the reaction.

Here we turn our attention to the synthesis of carboxylated PS particles with micrometer diameters by dispersion polymerization. We find, as reported previously, that simply adding small amounts of AA to the batch dispersion reaction causes a change in particle size and size distribution. Under some circumstances, simply delaying the addition of acrylic acid, mixed with more monomer and solvent, led to monodisperse particles. Attempts to increase the acid content of the particles in this way led to a loss of size control. In the sections below, we describe the steps necessary to regain control over particle size and maintain the narrow size distribution of carboxylated PS particles prepared by dispersion polymerization. Titrations of the particles in water provided information about the mean number of acid groups per particle at the particle surface.

Experimental Section

Reagents. All organic and polymeric reagents were used without further purification, including styrene (Aldrich), acrylic acid (AA, Aldrich), methanol, ethanol, poly(vinylpyrrolidone) (PVP) (Aldrich PVP55, $M_w = 55\,000$ g/mol and PVP360, $M_w = 360000$ g/mol), Triton X-305 (TX305, 70% solution in water, Aldrich), and 2,2′-azobis(2-methylbutyronitrile) (AMBN, Wako Pure Chemical Industries Ltd.). Water was purified through a Milli-Q purification system.

One-Stage Dispersion Polymerization. The standard recipe for the one-stage dispersion copolymerization of styrene with AA in ethanol is listed in Table 1. The following procedure was used: All the ingredients were added to a 250 mL three-neck reaction flask equipped with a condenser and a gas inlet. After a homogeneous solution formed at room temperature, the solution was deoxygenated by bubbling nitrogen gas at room temperature for 30 min. Then the flask was placed in a 70 °C oil bath and stirred mechanically at 100 rpm. The monomer conversion was monitored gravimetrically by removing aliquots during the polymerization.

Two-Stage Dispersion Polymerization. The standard recipe for the two-stage dispersion copolymerization of styrene with AA in ethanol is also listed in Table 1. The following procedure was used: All of the stabilizer (PVP), the co-stabilizer (TX305), and initiator (AMBN) and half of the monomer and ethanol were added to a 250 mL three-neck reaction flask equipped with a condenser and a gas inlet. After a homogeneous solution formed at room temperature, the solution was deoxygenated by bubbling nitrogen gas at room temperature for 30 min. Then the flask was placed in

Table 2. Effect of Acrylic Acid on the Particle Size and Size Distribution[d]

sample	AA, wt %	D, μm	CV, %	method	medium	solids content, %[c]	remark
O-1	0	2.0	<1	one-stage	ethanol	25	monodisperse
O-2	2	2.9	<3	one-stage	ethanol	25	uniform with some small particles
T-1	2	3.0	<1	two-stage	ethanol	25	monodisperse
TC-2	0	2.5	<1	two-stage	ethanol	25	monodisperse
T-2	4			two-stage	ethanol	25	90% aggregated, 1−5 mm hard aggregates
TC1−3	0	3.0	<2	two-stage	95% ethanol	25	monodisperse
T-3	4			two-stage	95% ethanol	25	90% aggregated, 1−5 mm loose aggregates
TC2−3[a]	4			two-stage	95% ethanol	25	90% aggregated, 1−5 mm loose aggregates
T-4	4			two-stage	95% ethanol	15	20% aggregated, 1−5 mm loose aggregates
T-8[b]	0	1−2	30	two-stage	95% ethanol	15	coagulum-free, polydisperse
T-6[b]	4	2.3	10	two-stage	95% ethanol	15	coagulum-free, uniform
T-7[b]	6	1.6	<1	two-stage	95% ethanol	15	coagulum-free, monodisperse
T-5[b]	0	1.4	<1	one-stage	95% ethanol	15	coagulum-free, monodisperse
T-9[a,b]	2	1.5	<1	two-stage	95% ethanol	15	coagulum-free, monodisperse
T-10[a,b]	4	1.6	<1	two-stage	95% ethanol	15	coagulum-free, monodisperse
T-11[a,b]	6	1.5	<1	two-stage	95% ethanol	15	coagulum-free, monodisperse

[a] 4 wt % AA (based on styrene) was added 1 h after the start of the reaction. [b] PVP360 was used in these experiments, while other experiments used PVP55. [c] Solids content in the first stage. CV = $(1/n)\sum_{i-1}^{n} |D_i - D_{av}|/D_{av}$, where D_{av} is the number-average diameter of all particles

Table 3. Two-Stage Dispersion Polymerization Reactions with PVP360[a]

	1st stage	2nd stage								
		T-5	T-12	T-13	T-8	T-6	T-7	T-9	T-10	T-11
AA amount (wt %)[b]		0	0	0	0	4	6	2	4	6
styrene (g)	3.0	0	3.0	3.0	3.0	3.0	3.0	0	0	0
AA (g)	0	0	0	0	0	0.24	0.36	0.06	0.12	0.18
ethanol (g)	16.15	0	16.15	16.15	16.15	16.15	16.15	7.6	7.6	7.6
water (g)	0.85	0	0.85	0.85	0.85	0.85	0.85	0.4	0.4	0.4
PVP360 (g)	0.135	0	0	0	0	0	0	0	0	0
TX305 (g)	0.15	0	0.30	0.60	0	0	0	0	0	0
AMBN (g)	0.12	0	0	0	0	0	0	0	0	0
D, μm		1.5	1.7	1.1	1.2	2.3	1.6	1.5	1.6	1.5
CV, %		<1	3	50	30	10	<1	<1	<1	<1

[a] The second-stage reactants were mixed, heated to the reaction temperature and then added 1 h after the start of reaction. [b] Based on total styrene in the reaction.

a 70 °C oil bath and stirred mechanically at 100 rpm. The AA was dissolved in the remaining styrene plus ethanol at 70 °C under nitrogen. After the polymerization reaction had run for 1 h, the hot AA solution in the other half of the monomer and ethanol was added into the reaction flask. The monomer conversion was monitored gravimetrically by removing aliquots during the polymerization. The reaction was continued for 24 h and the styrene conversion reached 90−95%.

One reaction was run in a 95/5 (w/w) ethanol/water mixture using PVP55 as the polymeric stabilizer. The hot AA solution in additional solvent without additional styrene was added into the reaction flask after the polymerization reaction had run for 1 h.

Many reactions were run at 15 wt % solids in 95% ethanol (w/w) as the reaction medium. The recipe for the reaction using PVP55 as the polymeric stabilizer is given on the right-hand side of Table 1. Another set of reactions employed PVP360 as a higher molar mass polymeric stabilizer. These recipes are summarized in Table 3.

Characterization of Particle Size and Size Distribution. The particle size was examined both by optical microscopy (Olympus, BX41) and scanning electron microscopy (SEM, Hitachi S-5200). To prepare samples for optical microscopy, the final polymer particle suspension was diluted with water, and a drop was placed on a clean glass microscope slide. The particle size and size distributions were examined by SEM. A particle-size histogram was constructed from measurements of 200−300 individual particles from the electron micrographs.

Titration. Titrations were carried out under a nitrogen atmosphere at 22 ± 1 °C and monitored with a conductivity meter (EcoMet Conductivity/Temp C65). Unless otherwise noted, all data were acquired from the forward (base-into-acid) titration. An aliquot (14.6 g, 10.7 wt % solids content) of the dispersion of carboxyl-containing PS particles was centrifuged to sediment the particles, and then the serum was decanted for serum titration using freshly prepared 0.025 M NaOH. The precipitated particles were redispersed in 95% ethanol to prepare a latex dispersion with 9.1 wt % solids content. A weighed sample of this suspension (2.2 g, 0.20 g of dry particles) was dissolved into 50 g of THF and titrated with freshly prepared 0.025 M NaOH. Another sample of this suspension (13.8 g, 1.26 g of dry particles) was diluted with 114 g of 95% ethanol to give a latex dispersion with 1.0 wt % solids content. This solution was also titrated with freshly prepared 0.025 M NaOH. Quantitative information was acquired from the titration plots using the standard extrapolation/intersection method to determine the titration end points.

Results and Discussion

Dispersion polymerization is defined as a polymerization in which the monomer and all other reactants are soluble in the reaction medium, but the polymer formed in the reaction is insoluble in the medium. Dispersion polymerization differs from precipitation polymerization in that the presence of a second polymer (the polymeric stabilizer) provides colloidal stability to the newly formed insoluble polymer particles and prevents coagulation. We use PVP as the polymeric stabilizer. There is good evidence that grafting occurs to the soluble polymer in these reactions, and the effective stabilizer is PVP containing PS grafts. There is also evidence that some ungrafted PVP adsorbs to the particles and aids in the steric stabilization of the particles during the reaction. Some researchers use a costabilizer in dispersion polymerization reactions. Anionic, cationic,[11] and nonionic surfactants have been used, as well as cetyl alcohol. There is conflicting evidence about whether this type of additive is needed. We have found that under our reaction conditions, including a small amount of TX305, an octylphenol ethoxylate, has little effect on the final particle size, but leads to a narrower particle size distribution. Thus, we include this costabilizer in all of our reactions. In the next two sections, we look at factors that affect the nature of the reaction outcome. We defer to the final section of this paper a discussion of the locus of the polymerized AA units in the system.

Low Acrylic Acid Content: Batch vs Two-Stage Process. In this section, we examine dispersion copolymerization of styrene with 2 wt % acrylic acid. We compare reactions in which all the reactants were added at the beginning with the two-stage process in which half of the monomer and solvent along with the entire AA was added after the end of the nucleation stage. The amount of AA is given as the wt % based on the total amount of styrene in the reaction. In these experiments, we used PVP55 with an estimated M_w of 55 000. On the basis of a large number of preliminary batch (one-stage) reactions in which we varied the amount of PVP55, we chose 16 wt % based on styrene. This represents the minimum amount of stabilizer that gave particles with a narrow size distribution.[26] An important observation for us is that when additional styrene and ethanol were added 30 min to 1 h after the start of the reaction, we still obtained particles with a very narrow size distribution, without adding additional PVP55 in the second stage. For the overall two-stage recipe in Table 1, the amount of PVP55 compared to total styrene is only 8 wt %.

In all of our reactions, the initiator AMBN was added to the reaction mixture at room temperature, and then the 250 mL flask containing the homogeneous reaction mixture was immersed into an oil bath at 70 °C. A comment is in order about this manner of initiating the reaction. A number of researchers have mixed monomer and all other reagents as we do at room temperature and then heated the reaction. Other groups, particularly those interested in reaction kinetics, preheat all the ingredients except initiator to the reaction temperature and then, at $t = 0$, add the initiator to the reaction. We have compared these approaches for reactions run without AA and found different final particle sizes. The second process gave somewhat larger particles (2.0 μm diameter) than the first process (1.6 μm).[27] In our hands, the former method led to better reproducibility. Thus, we employed this approach for all the reactions reported here. Of course, the temperature rise in the flask requires time. In one experiment, we monitored the increase in temperature in the reaction mixture. We found that the temperature reached 50 °C after 4 min, 60 °C after 6 min, and 65 °C after 9 min.

Parts A and B of Figure 1 show scanning electron microscopy (SEM) images of the PS particles prepared by the one-stage (batch) method following the recipe given in Table 1. In the absence of AA, the resulting particles were spherical with a diameter of 2.0 μm and a very narrow size distribution (CV < 1%). In an essentially identical reaction run in the presence of 2 wt % of AA, the average diameter of the resulting carboxylated PS particles increased to 2.9 μm, and the particle size distribution became broader (CV ≈ 3%). We also found that when 2 wt % of AA was added at the beginning of the reaction, the onset of turbidity took longer time, increasing from less than 10 min without AA to more than 20 min in the presence of AA. This is an indication, similar to that reported by Yang et al.,[21] that the presence of AA at the beginning of the reaction increases substantially the length of the nucleation stage.

Poly(acrylic acid) (PAA) is soluble in ethanol, and copolymers of AA with styrene are likely to be more soluble in ethanol than PS itself. Under these circumstances, the critical molecular weight at which the copolymer begins to precipitate will be larger than that of PS. In addition, it is possible that the rate of the adsorption of the stabilizer-grafted copolymers [PVP−P(styrene-*co*-AA)] onto the particles decreases, so that both the rate of particle formation and the amount of adsorbed grafted PVP decrease. These factors would lead to a longer nucleation time. This prolonged nucleation stage is believed to be responsible for the increase of the particle size and the broadening of the particle size distribution.[9,11,14,15]

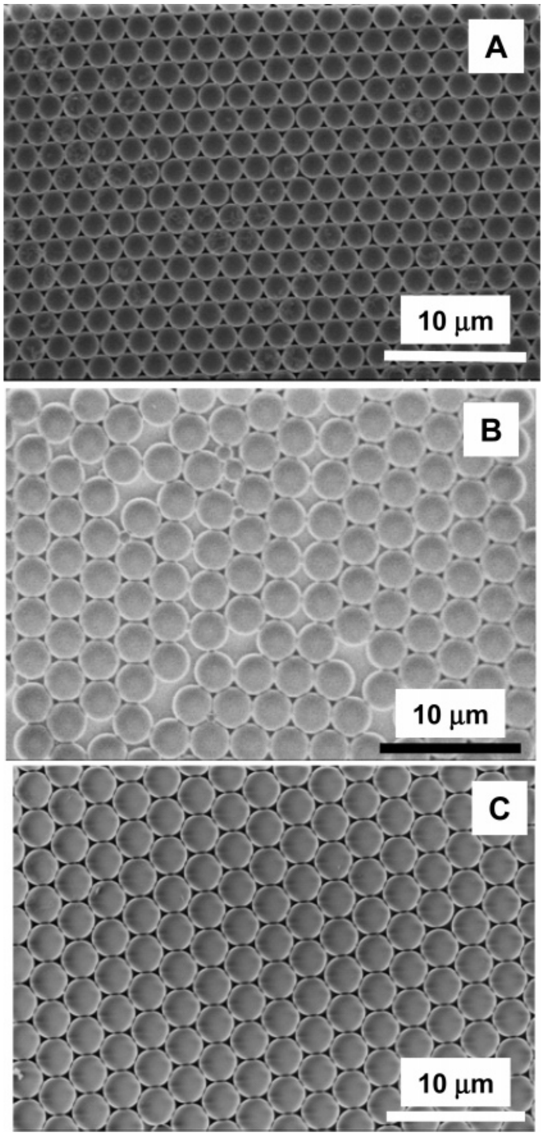

Figure 1. SEM images of PS particles prepared in ethanol by different processes according to Table 1. Key: (A) one-stage method without AA, (B) one-stage method with 2 wt % AA, and (C) two-stage method with 2 wt % AA.

In the two-stage reaction, the AA was dissolved in half of the monomer plus half of the total solvent. The mixture was preheated to the reaction temperature and then added 1 h after the start of the reaction. This was well after the onset of turbidity (10 min), but still at a low conversion (ca. 3 wt %). An SEM image of the product is shown in Figure 1C. These particles had a mean particle diameter of 3.0 μm and a very narrow size distribution (CV < 1%). For this reaction, delaying the addition of AA prevented this polar monomer from interfering with particle nucleation and yielded monodisperse particles.

The two-stage process also works well for reactions run in 95/5 ethanol/water (w/w) in which 2 wt % AA (based on total styrene) is added in the second stage. These reactions employed the two-stage recipe in Table 1, except for the change in reaction

Table 4. Surface Properties of Carboxyl Functionalized PS Microspheres Produced with Different Amounts of AA Added in the Second Stage

sample	AA in the feed (%)[a]	AA fraction on the surface (%)[b]	the surface area/-COOH ($Å^2$/COOH)	-COOH groups/nm^2	surface area coverage (%)
T-9	2	12.8	17.8	6	51
T-10	4	17.3	6.2	16	146
T-11	6	29.2	2.4	41	369

[a] Based on total styrene in the reaction. [b] Based on the total amount of AA in the reaction.

medium. This reaction also gave PS particles with an average particle diameter of 3.0 μm and a narrow size distribution (CV < 2%, sample TC1−3 in Table 2). This is one of the basic recipes we used in reactions described in the following section to study the effects of larger amounts of AA on the nature of the particles formed in the reaction.

We would like to comment on a curious feature of the PS particles shown in Figure 1C. Particles of this size, dispersed in ethanol, settle upon standing. Normally, sterically stabilized PS particles prepared by dispersion polymerization are easily redispersed upon gentle shaking. The particles described above containing 2 wt % AA were difficult to redisperse in ethanol after settling. In contrast, we were easily able to redisperse the carboxylated particles into water or into water−ethanol mixtures. This result suggests that the association of carboxyl groups in nearly anhydrous ethanol is stronger than in the presence of water, leading to stronger particle−particle association.

The Effect of Increased Amounts of AA in the Two-Stage Reaction. In this section, we report that the reaction outcome becomes considerably more complex when larger amounts of AA are employed in the reaction. Many combinations of reactants led to a loss of control of the reaction: coagulum formation, polydisperse particles, or nearly monodisperse particles containing a second population of small particles that may indicate secondary nucleation. A number of factors appear to be important. These include the composition of the reaction medium, the molecular weight of the PVP, and the details of delayed addition of AA to the reaction.

(a) Experiments with PVP55. For reactions run in ethanol as the solvent, when larger amounts of AA were added 1 h after the beginning of the reaction, useful particles no longer formed. For example, when 4 wt % AA (based on total styrene), mixed with styrene and ethanol was added, more than 90 wt % of the resulting polymer was present as a hard coagulum consisting of large aggregates with diameters ranging from 1 to 5 mm (T-2 in Table 4). Our working hypothesis, based on this finding, was that the styrene−acrylic acid copolymer formed in this reaction increased the interaction between particles. If the repulsion of PVP55 on the particle surface cannot overcome the attraction between particles, aggregation would occur.

To try to overcome this problem, we ran similar two-stage reactions in 95 wt % ethanol plus 5 wt % water. As described above, this recipe also gave monodisperse particles (but with a slightly broader size distribution) when 2 wt % AA plus styrene and solvent was added in the second stage. When we increased the amount of AA in the second stage to 0.5 g (4 wt % based on the total styrene) and added it along with additional styrene and solvent 1 h after the start of the reaction, we found that more than 90 wt % of the resulting polymer was present as a coagulum consisting of large aggregates with diameters ranging from 1 to 5 mm. In contrast to the reaction run in anhydrous ethanol, this coagulum consisted of loose aggregates (sample T-3 in Table 2).

To study the effect of AA on the colloidal stability of the resulting particles, we also carried out a two-stage reaction in which AA but no additional styrene was added in the second stage of the reaction. A solution of AA (4 wt % based on styrene) in 95 wt % ethanol was added in the second stage 1 h after the start of the reaction. This is a variation of the recipe in Table 1 in which the amounts added in the second stage are noted in parentheses in the middle column of Table. We found (TC2−3 in Table 3) that more than 90 wt % of the final polymer was present as a loose coagulum consisting of large aggregates with diameters ranging from 1 to 5 mm. We also noted that the particles formed early in the reaction were colloidally stable and precipitation occurred only after the monomer conversion reached 50%.

We then explored the effect of lower solids content on the colloidal stability of the resulting particles. In one experiment, we decreased the solids content from 25% to 15%. This recipe is given in the two right-hand columns of Table 1. The reaction product contained a stable dispersion of particles (sample T-4 in Table 2) plus ca. 20 wt % of a loose coagulum consisting of large aggregates with diameters ranging from 1 to 5 mm. While neither of these outcomes is satisfactory, we infer that the more polar medium and lower solids content are steps in the right direction.

Acrylic acid copolymers with styrene have a greater solubility in ethanol or 95% ethanol−water than polystyrene itself. We will see when we discuss titration experiments, that for reactions in which 4 or 6 wt % AA based on styrene are employed, a significant fraction of the −COOH groups are found in the serum phase. Yang et al.[21] have shown that the polymer becomes fully soluble in 95% ethanol at 70 °C when the reaction mixture contains greater than 10 wt % AA based on styrene. On the basis of other observations that we will describe in more detail below, we do not believe that the loss of the colloidal stability associated with the addition of 4 wt % AA is due to the increased solubility of the styrene−acrylic acid copolymer in our reaction. The origin of the colloidal instability is more likely related to interactions between carboxyl groups on different particles and insufficient steric stabilization. This is the type of interaction we put forward in the previous section to explain the difficulty in redispersing monodisperse carboxylated PS particles in ethanol that had sedimented on standing.

(b) Experiments with PVP360. We next turned our attention to the polymeric stabilizer. In the experiments described above, we used PVP55 as the stabilizer. The problems we experienced in adding more than 2 wt % AA to the two-stage reaction prompted us to examine a higher molecular weight stabilizer. We chose PVP360 as the stabilizer based on results reported by Yang et al.,[28] who investigated the effect of PVP360 concentration on particle size and size distribution for styrene polymerization in ethanol/water (80/5, w/w). They found that 2.5−6.5 wt % of this polymer, based on styrene, yielded particles with a narrow size distribution. For our experiments in ethanol/water (95/5, w/w) we chose a PVP360 concentration of 4.5 wt % based on the initial amount of styrene and also added 3.5 wt % (based on the initial styrene) TX305 to help the nucleation. The recipe is given in column T-5 in Table 3. The choice of adding TX305 was fortunate but largely intuitive. We found that the particle size distribution was very narrow; its CV was less than 1% (T-5 in Table 3, Figure 2A), whereas the CV reported by Yang et al.[28] was 14% at the same PVP360 concentration but without co-stabilizer. Because this recipe worked well, we did not explore the effect of PVP concentration on the particle size and size distribution. We did, however,

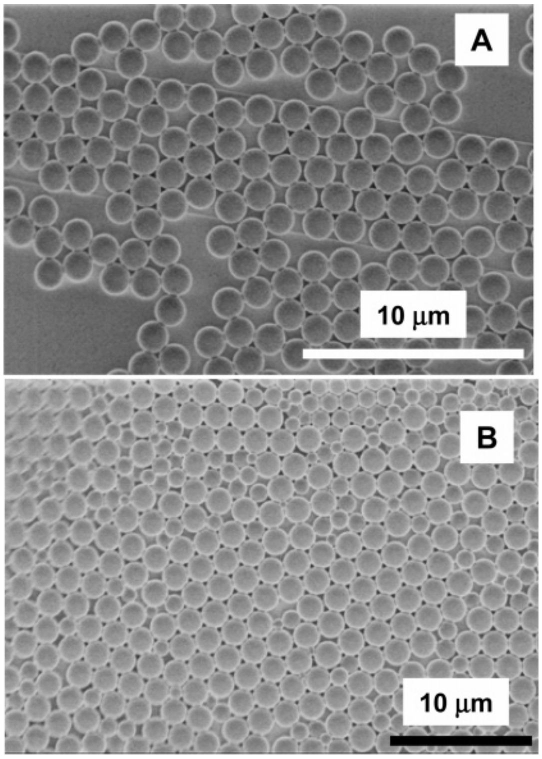

Figure 2. SEM images of PS particles prepared without acrylic acid using PVP360 as the stabilizer (two-stage reaction in ethanol/water 95/5 w/w) as described in Table 3. Key: (A) sample T-5, with no styrene addition in the second stage; (B) sample T-8, with styrene addition in the second stage.

examine the consequences of adding more styrene and solvent in the second stage, 1 h after the beginning of the reaction. Here we found that we lost control over particle size and size distribution, and a very polydisperse mixture of PS particles was obtained (sample T-8 in Table 3, Figure 2B). These two sets of reaction conditions serve as useful baseline conditions for investigating the influence of TX305 and AA on the post-nucleation polymerization reaction.

To study the influence of TX305 on the nature of the particles formed, we examined the consequences of adding different amounts of TX305 along with styrene and 95 wt % aqueous ethanol in the second stage of the reaction. In these reactions no acrylic acid was present. For the one-stage reaction (sample T-5 described above), monodisperse particles were obtained with a very narrow size distribution. When 3.0 g styrene and 17.0 g ethanol/water (w/w, 95/5) without any additional TX305 (sample T-8) were added 1 h after the start of the reaction, we found that the particles obtained were colloidally stable and coagulum-free, but these particles had a broad size distribution (CV $\approx$ 30%). Upon careful inspection of SEM images of these particles, we noted that the product consisted of ca. 50% (by number) monodisperse particles with a mean diameter of 2.0 μm, with the remaining product in the form of smaller polydisperse particles (Figure 2B). When 0.3 g TX305 (3.5 wt % based on total styrene, sample T-12) plus styrene and solvent was added 1 h after the start of the reaction, we found that the number of the smaller particles had decreased significantly (Figure 3A). The CV of the product (ca. 3%) was sufficiently small that these particles can be deemed "monodisperse". When a larger amount of TX305 (0.6 g, 7.0 wt % based on total styrene, sample T-12) was added along with styrene and solvent 1 h after the start of the reaction, we found that the number of the secondary particles had increased significantly (Figure 3B).

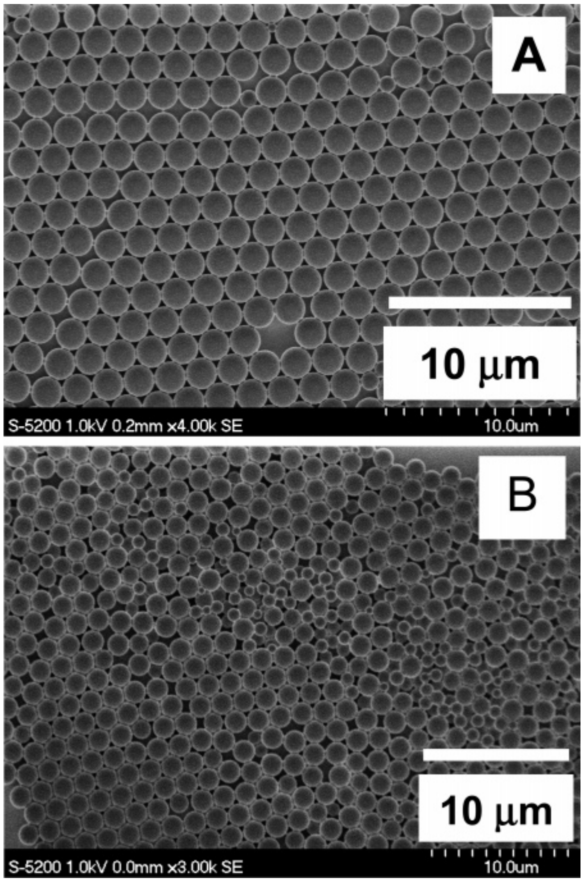

Figure 3. SEM images of PS particles prepared without acrylic acid using PVP360 as the stabilizer (two-stage reaction in ethanol/water 95/5 w/w) with an equal amount of styrene added in the second stage as described in Table 3. Key: (A) 3.5 wt % TX305 (based on the total styrene) added in the second stage; (B) 7.0 wt % TX305 added in the second stage.

The El-Aasser group has expressed the opinion[11] that the role of the co-stabilizer in narrowing the size distribution of polystyrene particles in ethanol is to decrease the aggregation rate of nuclei formed in the early stages of the reaction. If this assumption is correct, the co-stabilizer should also decrease the aggregation rate of oligomers or nuclei formed in the second stage. We imagine that there is a delicate balance of effects. A decrease in the aggregation rate of oligomers or nuclei in the second stage may allow existing particles to capture these oligomers or nuclei formed in the second stage before they aggregate to form secondary particles. This appears to be the effect of adding a small amount of additional TX305 in the second stage of sample T-12. Adding too much co-stabilizer may enhance secondary nucleation (sample T-13) by interfering with capture by existing particles. These results show that the proper co-stabilizer concentration in the second stage is crucial for prevention the formation of the secondary particles.

To study the influence of AA on the nature of the particles formed, we examined the consequences of adding different amounts of AA along with styrene and 95 wt % aqueous ethanol in the second stage (samples T-6 and T-7 in Table 3). When 4 wt % AA (based on total styrene, sample T-6) was added 1 h after the start of the reaction, the product was colloidally stable and coagulum-free. This result is in contrast with the finding for the reaction with PVP55 in which a similar amount of AA, styrene, and solvent added in the second stage led to coagulum. The resulting carboxylated particles here (sample T-6 in Table 3, Figure 4A) had a narrower size distribution compared to those obtained by the reaction with PVP360 but without AA. When

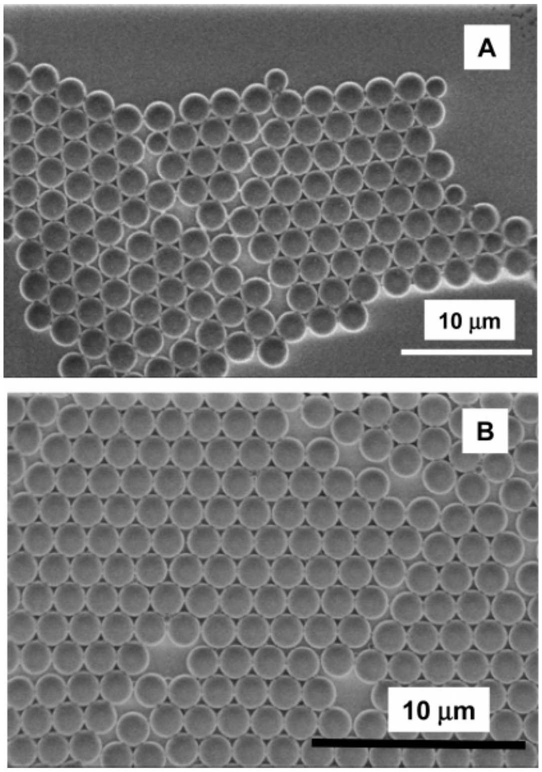

Figure 4. SEM images of PS particles with different AA content prepared using PVP360 as the stabilizer and ethanol/water (95/5 w/w) as the medium by the two-stage method according to Table 3. Key: (A) sample T-6, AA 4 wt %; (B) sample T-7, AA 6 wt %.

6 wt % AA was added under identical conditions, we obtained carboxylated PS particles with a very narrow size distribution (sample T-7 in Table 3, Figure 4B). In this two-stage methodology, the presence of additional AA in the reaction feed helped to prevent secondary nucleation and to promote the formation of monodisperse particles. This result is, of course, very different from that found when one increases the amount of AA in the monomer mixture in a batch reaction.

Our explanation of this effect remains speculative. In the presence of AA, a styrene–acrylic acid copolymer is formed. As mentioned above, the incorporation of AA into a styrene copolymer enhances the solubility of the copolymer in the reaction medium. While the polymer formed in the second stage precipitates in the reactions containing 4–6 wt % AA, its enhanced swellability compared to polystyrene may retard its self-aggregation to form secondary nuclei. In this sense, AA serves a similar role as co-stabilizers like TX305 to decrease the aggregation rate of the nuclei, to prevent the formation of the secondary particles, and to promote the capture of this polymer by particles present in the reaction. This effect is reminiscent of the results reported by Tseng et al.[13] and described in the Introduction for traditional dispersion polymerization of styrene in ethanol. In their hands, removal of the costabilizer led to a broad particle size distribution, but introduction of 1 wt % methacrylic acid into the initial monomer mixture provided enough additional stabilization for the system once again to produce particles of a uniform size.

Another way of looking at the results in Figure 2 is that the additional styrene added in the second stage may be a source of problems that might be avoided if one added only AA and additional solvent in the second stage. This insight turned out to be correct when PVP360 is used as the stabilizer. When 2, 4, or 6 wt % AA (based on styrene) in 95% ethanol was added to the respective reactions in the second stage, the resulting carboxylated PS particles were highly monodisperse (samples T-9, T-10, and T-11 in Table 3, Figure 5, parts A, B, and C). In addition, we note that the particle size remained the same as that of the reaction carried out without AA. This result emphasizes that the particle number had become constant, and remained constant, during the course of the reaction during which AA became incorporated. Thus, carboxylated PS particles can be prepared by the simple expedient of carrying out the reaction in 95% aqueous ethanol and adding up to 6 wt % AA in additional solvent to the reaction after the number of particles in the system became constant.

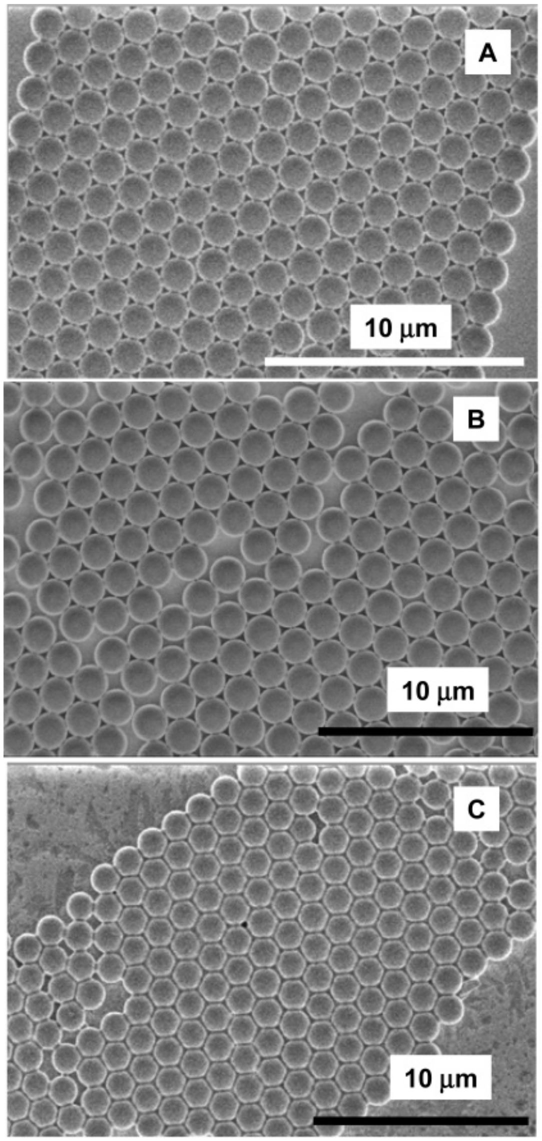

Figure 5. SEM images of PS particles with different AA content prepared using PVP360 as the stabilizer and ethanol/water (95/5 w/w) as the medium by two-stage method according to Table 3. Key: (A) T-9, AA 2 wt %; (B) T-10, AA 4 wt %; (C) T-11, AA 6 wt %.

This idea does not extend to particles synthesized with PVP55 as the stabilizer. When 4 wt % AA based on styrene was added in the second stage without additional styrene (cf., Table 1), most of the polymer formed appeared as coagulum rather than as colloidally stable polymer particles. Success in these reactions depends on finding a delicate balance between acrylic acid content and the effectiveness of the polymeric stabilizer.

Locus of the Carboxyl Groups. When AA is added to the reaction mixture, it copolymerizes with the remaining styrene in the system. If the copolymer formed is sufficiently acid rich,

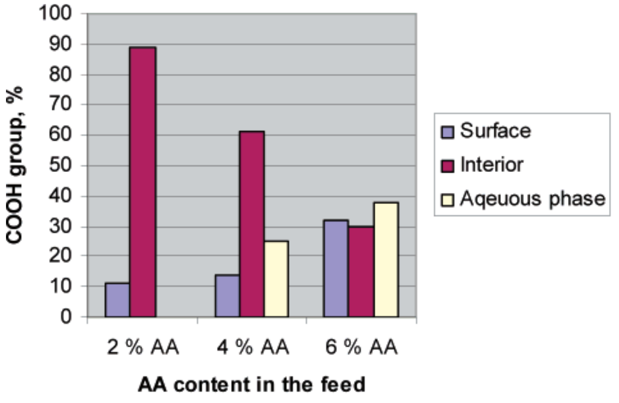

Figure 6. Distribution of acrylic acid groups (% mass of COOH groups) at different points in an emulsion system (interior and surface of particles, and in the aqueous phase) as a function of added AA amounts

it may remain in the serum phase and not become incorporated at all into the particles. If it is incorporated into the particles, it can either be buried in the interior or located in or at the surface. These three loci for the acid groups can be distinguished by titration. For a selected series of samples, the dispersions were centrifuged to separate the serum from the solids. Conductometric titration of the serum with 0.025 M NaOH gave the acid group content of the serum. The particle phase was resuspended in ethanol−water and divided into two portions. One portion was dissolved in tetrahydrofuran and titrated against NaOH to obtain the total −COOH group content of the particles. The remaining portion was titrated as a dispersed phase with NaOH. In this titration, one assumes that only those −COOH groups at the surface or buried just under the surface can react with aqueous base during the time of the titration. The results of these titrations are presented as histograms in Figure 6. We focus on the particles shown in Figure 5 (samples T-9, T-10, and T-11 in Table 3).

At 2 wt % AA, most of the carboxylic acid (89%) polymerized inside the particles, 11% of AA groups remained on the surface of the particles and very little AA-containing material remained in the serum. At 4 wt % AA, nearly 26% of the AA groups were found in the serum; 61% of the acid was found inside the particles, and 13% of all of the AA groups were on the surface of the particles. In the reaction in which 6 wt % AA based on styrene was employed, nearly 38% of the AA was found in the serum. Here 30% of the acid polymerized inside the particles, and 32% of the AA groups were detected on the surface of the particles. It is not surprising that with the increase of AA in the reaction, increasing amounts of AA units were found in the serum.

From an applications point of view, the important information is the number and nature of the titratable acid groups at the particle surface. In Table 4, we list the mean surface area per carboxylic acid group and surface coverage calculated for these particles assuming a smooth particle surface. For a given mean diameter of spherical particles, the particle number can be calculated from the mass of the dry sample divided by the mass of a single particle, calculated from the volume assuming the same density (1.04 g/mL) as bulk polystyrene. The total surface area of the particles was calculated from the surface area of a single particle times the particle number. The number of carboxylic acid groups on the surface was determined by conductometric titration. The mean surface area per carboxyl acid group was calculated by dividing the total surface area of all of the particles by the total number of carboxylic acid groups determined from the surface titration. For the particles containing 2 wt % AA, we calculate 17.8 Å^2 per −COOH group or 6 −COOH groups per nm^2. For the particles containing 4 wt % AA, we calculate 6.2 Å^2 per −COOH group or 16 −COOH groups per nm^2. A paper by Goodwin et al.[29] cites a value for the area occupied by a carboxyl group at the surface of a latex particle of 9 Å^2 (11 groups/nm^2). From this perspective, at 2 wt % AA for these 1.5 μm diameter particles, the surface coverage with −COOH groups is 51%. Whereas, at 4 wt % AA for these 1.6 μm diameter particles, the surface is completely covered with −COOH groups and a substantial fraction of these groups are part of acid-rich regions that are swollen by solvent.

For the sample prepared with the highest amount of AA, the number of carboxyl groups on the surface is much larger. For the sample prepared with 6 wt % AA in the feed, 62% of the AA present in the reaction was incorporated into the particles, and the fraction of titratable groups at the surface corresponds to 41 −COOH groups/nm^2. For these particles, we conclude that solvent-swollen chains of AA-rich copolymer protrude from the surface. These particles will be particularly interesting for applications in which one wants a large number of accessible carboxylic acid groups at the surface. For other applications in which near full surface coverage is sufficient, reaction conditions similar to those we employed with 2−3 wt % AA will be appropriate.

Summary

Addition of acrylic acid to the batch (one-stage) dispersion polymerization of styrene in ethanol led to a substantial increase of particle size and broadening of the particle size distribution. A sign that AA interferes with particle nucleation is given by the increase in time necessary for the reaction to turn turbid. From an operational perspective, we take the onset of turbidity as a qualitative indication that the nucleation stage is complete and the number of particles in the reaction has become constant.

Following previous practice that we employed for the synthesis of dye-labeled particles[30] and cross-linked particles[31] by dispersion polymerization,[25,32] we delayed the addition of AA until 1 h after the beginning of the reaction, well after the reaction turned turbid, and added the AA with additional monomer and solvent. This worked well for 2 wt % AA based upon total styrene, but for larger amounts of AA, a number of problems were encountered that led to a broader size distribution. For reactions containing 2, 4, or 6 wt % AA based on styrene, these problems could be overcome by carrying out the reaction in 95/5 ethanol/water (w/w), at a reduced solids content, employing a higher molecular weigh poly(vinylpyrrolidone) (PVP360) sample as the stabilizer, and adding the AA in solvent without additional styrene. In this way we obtained carboxylated PS particles with a mean diameter of 1.5 μm, a CV of less than 1%, and a carboxyl content that varied with the amount of AA in the feed.

For the sample prepared with 2 wt % AA, essentially all the AA added became incorporated into the particles, with 11% of the AA added located at the surface as indicated by titration with aqueous base. This corresponds to approximately 6 −COOH groups per nm^2, or 51% surface coverage. For the samples prepared in the presence of 4 and 6 wt % AA based on styrene, a substantial fraction of the acid groups were present in a serum-soluble form. Titrations indicated a rather high concentration of carboxylic acid groups at the particle surface. We infer that these groups are present in the form of solvent-swollen copolymer chains attached to the particle surface.

The addition of AA in the two-stage dispersion polymerization, on one hand, helps to prevent the secondary nucleation.

On the other hand, the existence of carboxyl groups on the surface of the particles tends to increase the attraction between particles and cause the particle aggregation.

Acknowledgment. We thank Clariant Corporation, Clariant Canada, NSERC Canada, and the Province of Ontario through its ORDCF program for their support of this project. J.-S.S. thanks the Province of Ontario for an OGS scholarship.

References and Notes

(1) Kinato, H.; Nakamura, K.; Ise, N. *J. Appl. Biochem.* **1982**, *4*, 34.
(2) Clonis, Y. *J. Chromatogr.* **1987**, *179*, 407.
(3) Kamei, S.; Okubo, M.; Matsuda, T.; Matsumoto, T. *Colloid Polym. Sci.* **1987,** *264*, 743.
(4) Wang, Y. M.; Feng, L. X.; Pan, C. Y. *J. Appl. Polym. Sci.* **1998**, *70*, 2307.
(5) Chattha, M. S.; Theodore, A. N. *J. Coat. Technol.* **1985**, *57*, 721.
(6) Chen, S. A.; Lee, S. T. *Macromolecules* **1991**, *24*, 3340.
(7) Ugelstad, J.; Kaggerud, K. H.; Hansen, F. K.; Berge, A. *Makromol. Chem.* **1979**, *180*, 737.
(8) Lok, K. P.; Ober, C. K. *Can. J. Chem.* **1985**, *63*, 209.
(9) Paine, A. J.; Luymes, W.; McNulty, J. *Macromolecules* **1990**, *23*, 3104.
(10) Shen, S.; Sudol, E. D.; El-Aasser, M. S. *J. Polym. Sci., Part A: Polym. Chem.* **1993**, *31*, 1393.
(11) Shen, S.; Sudol, E. D.; El-Aasser, M. S. *J. Polym. Sci., Part A: Polym. Chem.* **1994**, *32*, 1087.
(12) Takahashi, K.; Miyamori, S.; Uyama, H.; Kobayashi, S. *J. Polym. Sci., Part A: Polym. Chem.* **1996**, *34*, 175.
(13) Tseng, C. M.; Lu, Y. Y.; El-Aasser, M. S.; Vanderhoff, J. W. *J. Polym. Sci., Part A: Polym. Chem.* **1986,** *24*, 2995.
(14) Ober, C. K.; Lok, K. P. *Macromolecules* **1987**, *20*, 268.
(15) Horák, D.; Śvec, F.; Fréchet, J. M. J. *J. Polym. Sci., Part A: Polym. Chem.***1995**, *33*, 2329.
(16) Sáenz, J. M.; Asua, J. M. *J. Polym. Sci., Part A: Polym. Chem.* **1996**, *34*, 1977.
(17) Sáenz, J. M.; Asua, J. M. *Macromolecules* **1998**, *31*, 5215.
(18) Cao, K.; Li, B.; Pan, Z. *Macromol. Symp.* **2000**, *150*, 195.
(19) Winnik, F. M.; Ober, C. K. *Eur. Polym. J.* **1987**, *23*, 617.
(20) Ahmad, H.; Tauer, K. *Colloid Polym. Sci.* **2003**, *281*, 686.
(21) Yang, W. L.; Yang, D.; Hu, J. H.; Wang, C. C.; Fu, S. K. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 555.
(22) Yasuda, M.; Seki, H.; Yokoyama, H.; Ogino, H.; Ishimi, K.; Ishikawa, H. *Macromolecules* **2001**, *34*, 3261.
(23) Yasuda, M.; Yokoyama, H.; Seki, H.; Ogino, H.; Ishimi, K.; Ishikawa, H. *Macromol. Theory Simul.* **2001**, *10*, 54.
(24) Lu, Y. Y.; El-Aasser, M. S.; Vanderhoff, J. W. *J. Polym. Sci., Part B: Polym. Phys.* **1988**, *26*, 1187.
(25) Song, J. S.; Tronc, F.; Winnik, M. A. *J. Am. Chem. Soc.* **2004**, *126*, 6562.
(26) With less PVP55 present in the reaction, we obtained a significant fraction of the product as a precipitate consisting of aggregated particles. When more PVP55 was used, the particle size became smaller.
(27) Song, J. S. Ph.D. dissertation, University of Toronto, Toronto, ON, Canada, 2006.
(28) Yang, W. L.; Hu, J. H.; Tao Z. H.; Li, L.; Wang, C. C.; Fu, S. K. *Colloid Polym. Sci.* **1999,** *277*, 446.
(29) Goodwin, J. W.; Hearn, J.; Ho, C. C.; Ottewill, R. H. *Colloid Polym. Sci.* **1974**, *252*, 464.
(30) Song, J. S.; Tronc, F.; Winnik, M. A. *Polymer* **2006**, *47*, 817−825.
(31) Song, J. S.; Winnik, M. A. *Macromolecules*, **2005**, *38*, 8300.
(32) Song, J. S.; Winnik, M. A.; Metz, H. J.; Graciet, J. C. WO05026225A1 (to Clariant International Ltd).

MA052330F